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Emittance and Absorptance of NASA Ceramic Thermal Barrier Coating System

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EMITTANCE AND ABSORPTANCE OF NASA CERAMIC THERMAL BARRIER COATING SYSTEM*

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SUMMARY

Normal spectral emittance measurements were made on a two-layer ceramic thermal barrier coating system developed at the NASA Lewis Research Center. This system consists of a metal substrate, a NiCrAlY bond coating, and a yttria-stabilized ceramic coating. The normal spectral emittance was used to calculate the thermal radiation properties of hemispherical total absorptance and emittance of the NASA coating system.

The normal spectral emittance of the coating system was obtained at a single bond coating thickness of 0.010 centimeter, at ceramic coating thicknesses of zero to 0.076 centimeter, at wavelengths of 0.4 to 14.6 micrometers and at temperatures of 300 to 1590 K. These data were transformed into hemispherical total emittance values and correlated with respect to ceramic coating thickness and temperature using multiple regression curve fitting techniques. Equations were obtained which can be easily used by a designer to calculate the coating system hemispherical total absorptance at temperatures of 700 to 2800 K and the coating system hemispherical total emittance at temperatures of 700 to 1590 K. The data show that the NASA coating system is highly reflective and therefore can significantly reduce radiation heat loads on cooled gas turbine engine components.

Calculation of the radiant heat transfer within the nonisothermal, translucent ceramic coating material shows that a designer, with little loss of accuracy, can use the gas-side ceramic coating surface temperature in heat transfer analysis of radiation head loads on the coating system.

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INTRODUCTION

The spectral emittance of stabilized zirconia ceramic thermal barrier coating systems is needed for evaluating the radiant heat loads on coated gas turbine engine parts. Analytical predictions of spectral emittance are difficult because this ceramic material is porous and translucent. Also, the optical properties of the stabilized zirconia have not been measured in sufficient detail for use in rigorous analysis of radiation within this material. Because of these difficulties, the spectral emittance of the zirconia ceramic coating system was measured over a range of temperatures that would be typical of its use on cooled coated gas turbine components.

Use of "white" ceramic oxides such as stabilized zirconia in thermal barrier coating systems provides a heat barrier because, in addition to having low thermal conductivities, the white oxides are good reflectors of radiant heat flux at wavelengths of 1 to 5 micrometers (ref. 1). Compared to oxidized metals, these oxides can reflect two to three times more heat flux and, therefore, substantially contribute to the reduction of radiant heat load (radiant energy absorbed minus that emitted). The lower heat loads will reduce metal temperatures and cooling requirements resulting in increased engine durability and better performance.

Many investigators have measured the spectral emittance of white ceramic oxide materials but the data spread is wide. Reference 1 presents data which shows that this spread may be attributed to ceramic material translucence. As a consequence, emittances of thermal barrier coating systems depend on emittances of both the ceramic translucent layer and of the materials underneath. Another reason for the spread of spectral emittance data is that there are temperature drops through the translucent ceramic layer which will result in emittance measurement variation.

A study was conducted to measure the normal spectral emittance of a ceramic thermal barrier coating system of current wide interest. This coating system, developed at the NASA Lewis Research Center (refs. 2 to 7), consists of a metal substrate, a layer of NiCrAlY bond coating, and a layer of yttria-stabilized zirconia ceramic coating. In this study, the effect on emittance of variables such as thermal barrier coating system temperature and ceramic coating thickness were measured. Also measured was the effect of angle of heat emission and the effects of ceramic stabilizer, roughness and color. The emittances of a coated, air-cooled blade before and after tests in a research engine were also measured.

Emittance data on the NASA Ceramic Thermal Barrier Coating system were obtained in the visible and infrared wavelength regions with a spectrometer, a reflectometer, and a radiation pyrometer at a single bond coating thickness of 0.010 centimeter, and at six ceramic coating thicknesses of zero, 0.015, 0.025, 0.0330, 0.051, and 0.076 centimeter. System normal emittance data were obtained at wavelengths of 0.4

to 14.6 micrometers and at system temperatures of 300, 773, 1265, 1530, and 1590 K. For the ceramic coating material only, a normal spectral emittance at 900 K and transmittance at 300 K were measured. Data are presented as plots of normal emittance, reflectance, and transmittance against wavelength at the various ceramic thicknesses and temperatures.

The coating system data were transformed into total hemispherical emittance values and correlated with respect to ceramic coating thickness and temperature using multiple regression curve fitting techniques. Equations were obtained which can be used to calculate the system hemispherical total absorptance over a temperature range of 700 to 2800 K and system hemispherical total emittance over a range of 700 to 1590 K. The effect of ceramic coating translucence and temperature drop through the coating on system radiant heat transfer is also presented.

ANALYSIS

This section shows how the total hemispherical emittance and absorptance of the NASA Ceramic Thermal Barrier Coating (TBC) system was calculated using measured values of the normal spectral emittance. The temperature at which this system radiates is also defined.

Hemispherical Total Emittance and Absorptance

Emittance is the ratio of heat flux radiated from a specimen to the heat flux radiated from a blackbody at the same temperature. This property is defined as the normal spectral emittance when values are obtained at various wavelengths by viewing the radiating surface in a normal direction. When the directional heat flux follows Lambert's cosine law, then the directional spectral emittance is shown analytically and experimentally in reference 8 to be independent of the angle toward the surface normal and identical with the hemispherical spectral emittance. The validity of this relation for the TBC is verified by experiments made herein.

To obtain the hemispherical total emittance, the hemispherical spectral emittance, assumed equal to the measured normal spectral emittance, is integrated with respect to wavelength (ref. 9) in the following way:

$$\varepsilon'_{h,t} = \frac{b_1 T_c}{\sigma} \int_0^\infty \varepsilon'_{h,\lambda,T_c} \left(\frac{W_\lambda}{W_{\lambda_m}} \right)_{T_c} d\lambda \qquad (1)$$

The quantity $\varepsilon'_{h,\lambda,T_c}$ given in equation (1) generally depends on both wavelength and temperature of the system. The ratio W_λ/W_{λ_m} depends upon the product λT_c which is tabulated in reference 9. (All symbols are defined in the appendix.)

In this analysis, the system hemispherical spectral emittance, $\varepsilon'_{h,\lambda,T_c}$ was assumed to be temperature invariant. This assumption is reasonable because the normal spectral emittance of the bond coating and of white ceramic oxides such as stabilized zirconia or very pure aluminum oxide is only a weak function of temperature (refs. 1 and 10). This assumption was also verified in this study.

However, equation (1) shows that the hemispherical total emittance $\varepsilon'_{h,t}$ will vary with temperature. Numerical procedures were used to perform the integrations of equation (1). Hemispherical total emittances were correlated with respect to coating thickness and isothermal temperature using multiple regression curve fitting techniques.

The hemispherical total absorptance, defined in terms of the hemispherical spectral emittance and incoming blackbody radiation is

$$\alpha'_{h,t} = \frac{b_1 T_s}{\sigma} \int_0^\infty \varepsilon'_{h,\lambda,T_c} \left(\frac{W_\lambda}{W_{\lambda_m}} \right)_{T_s} d\lambda \tag{2}$$

The same assumptions relating to $\varepsilon'_{h,\lambda,T_c}$ in equation (1) apply for equation (2).

Comparison of equations (1) and (2) shows that, when the hemispherical total emittance is evaluated at the gas source temperature,

$$\alpha'_{h,t} = \varepsilon'_{h,t} \tag{3}$$

Equation (3) provides a method for determining hemispherical total absorptance values from hemispherical total emittance data. Equation (3) is valid only when the incident heat flux has a spectral distribution proportional to that of a blackbody source at a temperature, T_s, with incident fluxes which are independent of angle (ref. 11). This (gray gas) assumption is usually applied in practical design problems associated with current gas turbine engine combustors and turbines. This assumption can be closely realized in such hardware because gas pressures are high and, therefore, combustion gas volumes have a large amount of soot in them (ref. 12). Reference 13 shows that total flame emissivity can be as high as 0.9 at a combustion gas pressure of 2×10^6 pascals. Rigorous calculation of radiation heat transfer from a sooty flame is extremely complex; recent advances toward achieving complete solutions to this problem are discussed in reference 14.

Coating Translucence

Isothermal heat balance equations are developed for ceramic coating spectral transmittance in terms of both ceramic coating and TBC system spectral emittances. These equations are used to verify experimental accuracy. Then, for nonisothermal conditions, equations are developed for determining the total effective temperature at which the thermal barrier coating system radiates. The total effective temperature is then compared to the gas-side TBC surface temperature to determine which temperature is more practical for use in prediction of TBC total heat flux.

Isothermal conditions. - The microstructure of the TBC and a schematic of the radiant heat flow through the porous and translucent stabilized zirconia ceramic coating is shown in figures 1 and 2, respectively. A heat balance equation modeling isothermal radiation for the TBC at various wavelengths is

$$(\varepsilon'\overline{W})_{n,\lambda} = \left(W_0\varepsilon_0\tau_1 + W_1\varepsilon_1\right)_{n,\lambda} \tag{4}$$

It is assumed that the emittance and transmittance terms include internal scattering effects within the ceramic coating volume. The blackbody radiant intensity is given by reference 9 as

$$W_\lambda = C_1/\lambda^5\left(e^{C_2/\lambda T} - 1\right) \tag{5}$$

The term on the left side of equation (4) is the net radiant heat flux leaving the translucent ceramic coating. The first term in the parenthesis on the right of equation (4) is the rate at which the filled bond coating layer emits heat flux through the thickness of the translucent ceramic material located above the filled bond coating surface (fig. 2). The second term is the rate at which only the ceramic material located above the filled bond coating surface radiates heat flux. The first and second terms are added to give the total heat flux emitted at wavelength λ from the two coating layers.

At isothermal conditions, blackbody radiant intensities are equal throughout the TBC coating layers, and the heat balance can be written in terms of the emittance and transmittance properties as follows:

$$\varepsilon'_{n,\lambda} = \left(\varepsilon_0\tau_1 + \varepsilon_1\right)_{n,\lambda} \tag{6a}$$

Rearrangement of equation (6a) gives the following required equation for calculating $\tau_{1,n,\lambda}$ using experimental emittance measurements:

$$\tau_{1,n,\lambda} = \left[(\varepsilon' - \varepsilon_1)/\varepsilon_0\right]_{n,\lambda} \tag{6b}$$

The transmittance obtained with this modeling was compared with directly measured values of transmittance. The transmittance includes scattering effects on the porous ceramic coating volume.

Nonisothermal conditions. - The physical properties of the yttria stabilized zirconia ceramic used in the TBC combine to make thermal gradients a potential problem in the evaluation and use of its thermal radiation properties. Ceramic plasma-sprayed materials scatter energy and, therefore, are translucent. Hence, these materials emit and absorb thermal radiation from a surface layer of appreciable thickness. When such a ceramic layer has a large thermal gradient, there is no unique temperature (such as the surface temperature with opaque metals) to use in radiant heat flux calculations. In this case, an effective total temperature $\overline{T}$ can be defined for heat transfer calculations.

To illustrate the procedure for calculation of the TBC effective total temperature $\overline{T}$, the ceramic thickness above the filled bond coating has been analytically divided into four equal subvolumes as illustrated in figure 3. Using the Bouguer-Lambert law of absorption (ref. 9), the associated heat balance is

$$(\varepsilon'\overline{W})_{n,\lambda} = \left(W_0\varepsilon_0\tau^4 + W_1\varepsilon_1\tau^3 + W_2\varepsilon_2\tau^2 + W_3\varepsilon_3\tau + W_4\varepsilon_4\right)_{n,\lambda} \tag{7}$$

Linear temperature drops were assumed through the ceramic material, and the emittances and transmittances are assumed invariant with temperature.

Values of $(\varepsilon'\overline{W})_{n,\lambda}$ may be integrated over wavelength to obtain the effective total heat flux $\overline{Q}$ radiating from the TBC. The effective total temperature T is then evaluated from the fourth-power law as follows:

$$\overline{T} = \left(\frac{\overline{Q}}{\sigma\varepsilon'_{h,t,\overline{T}}}\right)^{0.25} \tag{8}$$

The conditions selected for an example calculation are representative of a current aircraft gas turbine engine with the TBC applied to cooled turbine blades. A ceramic thickness of 0.020 centimeter was assumed. The gas-side ceramic surface temperature and filled bond coating average temperature were assumed to be 1356 and 1242 K, respectively (fig. 3). The temperature drop through the ceramic was assumed to be linear since references 15 and 16 show that yttria-stabilized zirconia thermal conductivity is nearly constant (1.5±0.1 W/(m)(K) over a temperature range of 1200 to 2260 K).

APPARATUS AND PROCEDURE

Table I presents the materials, experimental conditions, and instruments for obtaining isothermal spectral emittance measurements. Data were obtained over thermal radiation temperature and wavelength ranges of 300 to 1590 K and 0.4 to 14.6 micrometers with three instruments. A spectrometer was used to obtain data continuously and isothermally over a broad range of temperature and wavelength. Radiation pyrometer and integrating sphere reflectometer instruments were used to extend and confirm the data obtained with the first instrument.

Instruments and Specimens

Spectrometer. - Figure 4 presents schematic drawings of the experimental arrangement for the spectrometer. The spectrometer consists of a double-beam spectrophotometer instrument with blackbody and emittance furnace attachments. The blackbody furnace is a heated cavity (fig. 4(b)) which is constructed to closely approximate the characteristics of a perfect blackbody thermal radiator which ideally has an emissivity equal to 1 with no temperature gradient along the wall surface. The specimen furnace accepts sample disks and heats these samples to the desired isothermal temperature. A radiant heat emission area of about 1 cm^2 is the source for the specimen energy beam while a heat emission area of equal size on the blackbody furnace wall serves as the reference source. The specimen and blackbody radiant energies are focused with mirrors into a sodium chloride prism (fig. 4(a)). Spectral energy output is sensed with a thermocouple detector. By establishing and maintaining the same set point temperature for both the sample and the blackbody wall surface, an absolute measurement of the normal spectral emittance of the sample is obtained from the ratio of sample-to-blackbody energy output.

To obtain transmittance values, the measured radiant energy output through a ceramic specimen (at a temperature of about 700 K) in a beam originating at the blackbody wall surface is divided by the output detected without a specimen in the beam. Reflectance was not measured with this instrument, but may be calculated from the following relation:

$$r_{n,\lambda} = \left(1.0 - \varepsilon_n - \tau_n\right)_\lambda \tag{9}$$

Most experimental emittance measurement difficulties result from a mismatch of specimen and blackbody temperatures because small temperature gradients are always present. Therefore, calibration of the instrument is necessary. High purity alumina (99.5 percent Al_2O_3) plasma-sprayed to a thickness of 0.051 centimeter onto Inconel

alloy 718 disks was used as a standard for calibration. The ceramic is opaque at this thickness and no radiation from the Inconel will pass through the ceramic. Figure 5 shows the normal spectral emittance obtained at alumina standard and blackbody temperatures (thermocouple 1, fig. 4(b)) of 773, 1265, and 1530 K. At each temperature, measurements were made over an infrared wavelength range of 1.2 to 14.7 micrometers. Repeatability of emittance was within 2 percent of full-scale value. No variation of emittance with temperature was noted. Data obtained from the literature (refs. 1 and 17) generally agree with the spectrometer data within 3 percent of full-scale value. Measured temperature drops through the standard were less than 2 K at all temperatures investigated, and temperature variations along the blackbody wall were less than 10 K. These temperature conditions are defined herein as isothermal.

After instrument calibration had been established, the TBC normal spectral emittance data with rough and smoothed yttria stabilized coated specimens were measured at the same infrared wavelengths covered during calibration procedures. Measurements were made at 773, 1265, and 1530 K at each TBC ceramic thickness (measured above the ceramic filled bond coating, fig. 2) of 0, 0.015, 0.025, 0.033, 0.051, and 0.076 centimeter. Other details of TBC experimental conditions including other types of zirconia stabilizer, various ceramic colors, type of substrate and ceramic surface condition are given in table I. The details of emittance measurements of the alloy bond coating, of emittance and transmittance of only yttria-stabilized zirconia (without bond coating and substrate), and of a coated sample taken from the pressure surface of a blade tested in a research engine are also included in table I.

Infrared radiation pyrometer. - This instrument (fig. 6) is designed to operate between 350 and 1900 K at a wavelength of about 2.3 micrometers. Measurements were made by sensing the infrared radiation emitted by a 0.03 cm^2 circular projected area of the sample surface. This radiated energy is transduced into an electrical output within the instrument which is displayed as an emittance reading at known specimen temperatures. A 99-percent pure alumina standard, fabricated by plasma-spraying alumina to a thickness of 0.050 centimeter onto a platinum substrate, was used to obtain alumina emittance measurements in a brick-lined electric furnace at isothermal temperatures of 1265, 1530, and 1700 K. Calibration with the spectrometer data presented in figure 5 is within 3 percent.

Metal disks were coated with the TBC and heated in the spectrometer emittance furnace to temperatures of 773 and 1530 K (table I). The pyrometer was used to measure the emittance of these specimens at angles of 0° to 80° from the normal to the surface of rough and polished ceramic with thicknesses of 0, 0.025, and 0.051 centimeter. In another test, the coating was plasma-sprayed onto a research engine blade surface, smoothed to ceramic thicknesses of 0.025 and 0.051 centimeter, and heated in a brick-lined electric furnace to uniform temperatures of 773, 1265, and 1590 K

(table I). The furnace control thermocouple and a thermocouple in the blade metal wall were used for temperature measurement. Emittance measurements were made at angles of 0^{o} to 88^{o} from the normal to the surface at the leading edge region. The blade was uncooled during these measurements.

Integrating sphere reflectometer. - Figure 7 shows a schematic of this reflectometer (ref. 18). Measurements were made by illuminating a sample with monochromatic radiant energy from a tungsten strip filament lamp. This energy impinges on a sample mounted in the integrating sphere and is reflected to the wall of the sphere which is coated with white ceramic magnesium oxide. The sphere wall reflects the radiation, and a small amount falls on the detector and is amplified and recorded.

For calibration purposes, the reflectance of the reference plasma-sprayed, polished alumina sample described in the section Spectrometer was measured at temperatures and wavelengths of 300 K and 0.4 to 1.4 micrometers, respectively. The reflectance was converted to emittance by subtracting the reflectance from unity; the values are shown in figure 5. At 1.2 micrometers, where data taken with the reflectometer and spectrometer overlap, agreement is within 1 percent of full-scale value.

This reflectometer was used at 300 K to obtain the emittance of the TBC with smoothed zirconia at thicknesses of 0 and 0.051 centimeter and at wavelengths of 0.4 to 1.4 micrometers (table I). Reflectances at temperatures above 300 K were not obtained with this reflectometer.

Test Engine

A research gas turbine engine (ref. 5) was used to evaluate the effect of deposition of combustion products and particulate matter on the normal spectral emittance of the TBC on an air-cooled turbine blade. The effect was evaluated as part of another research test and the operating conditions and number of starts and stops were, as a result, partially influenced by the other test. The coated blade was usually operated at a turbine inlet temperature of 1367 to 1644 K and at a gas pressure of 3.04×10^{5} pascals. After the engine tests, a specimen of the coating was cut from the blade pressure surface near the trailing edge, and the specimen emittance was measured. The ceramic on this part of the blade had the greatest amount of deposits from the combustion gases.

Coating Equipment

Commercial grit-blasting equipment was used to clean and roughen the metal substrate surfaces. A hand-held plasma-spray gun was used to apply powders of bond and ceramic materials to the metal and bond surfaces. In the gun, an electric arc was

contained within a water-cooled nozzle. Argon gas passed through the arc and was excited to temperatures of about 17 000 K. The bond and ceramic powders were mechanically fed into the nozzle where they were almost instantaneously melted.

Thermal Barrier Coating Preparation

Coating deposition and description. - Metal substrate surfaces were first grit blasted with commercial white alumina material. Inlet supply pressure to the blasting equipment was about 7×10^5 pascals, and grit impingement was nearly normal to the surface. Alumina grit size was 250 micrometers, and surface roughness after grit blasting was about 6 micrometers rms. Within 30 minutes after roughening, NiCrAlY bond coating (table I) was plasma-sprayed onto the roughened metal surfaces to thicknesses of 0.010 centimeter. Particle sizes of the bond material fed into the plasma spray gun were 44 to 74 micrometers, and the roughness of the bond coating was 5 micrometers rms. Roughness was measured with a commercial surface roughness meter.

Within 30 minutes after bond coating application, zirconia stabilized with either yttria, magnesia, or calcia was applied to coating thicknesses shown in table I. Yttria- and magnesia-stabilized zirconia particle sizes were 44 to 74 micrometers and calcia-stabilized particle size was 105 to 10 micrometers. Roughness of these ceramic coatings was 8 to 10 micrometers rms and 1 to 3 micrometers rms before and after polishing, respectively. Polishing was done with an alumina rod, and dust residues were removed with a clean air blast. Coating thickness was measured with micrometer calipers during deposition. The plasma-spray gun was held nearly perpendicular to the surfaces at distances of about 15 centimeters and 10 centimeters for the bond and ceramic coating applications, respectively. The resulting microstructure and porosity of the two-layer coating is shown in figure 1 which was reproduced from reference 5. Substrate temperature did not exceed 420 K during plasma-spray deposition.

The color of plasma-sprayed, yttria-stabilized zirconia varied from light yellow to light yellow orange with minute black specks distributed throughout the ceramic. Specimens with these colors were prepared for study. Reference 3 indicates that coatings so colored are adherent and are good thermal barriers on jet engine components.

TBC metal substrates and thermocouple attachment. - For emittance measurements with the spectrometer, substrate specimens were fabricated from 1.6-millimeter-thick sheet stock into 23-millimeter-diameter disks. A Chromel-Alumel thermocouple fabricated from 0.13-millimeter-diameter electrically insulated wire was mounted in a small groove machined into the back of the disks. Thermocouple junctions were spot-welded at the center of the disk and the thermocouple wires were held in the grooves with a high temperature alumina cement. This attachment procedure minimized heat conduction through the wires because a long length of thermocouple element is buried

in an isothermal surface. Except for the specimen cut from the coated blade, all substrates were fabricated from Inconel 718 sheet stock. Blade metal wall material was cast B-1900.

For measurements with the reflectometer, substrates were fabricated from Inconel 718 and were the same dimensions as the spectrometer substrates. Specimen temperatures were also measured with thermocouples mounted in grooves machined into the back of the disk.

For the pyrometer tests, research blades were fabricated from cast B-1900 and disk specimens were made from Inconel 718. As with other tests, thermocouples were mounted in grooves machined into the blades and disks.

Preparation of zirconia ceramic disk specimens without bond coating and metal substrate. - Yttria-stabilized zirconia disks for emittance measurements were formed by plasma-spraying zirconia onto roughened aluminum substrates (no bond coating was used). The ceramic was then removed in one piece by heating the coated substrates to 900 K and then quenching in water at 300 K. These ceramic specimens were placed onto polished aluminum substrates which had a measured emittance of 0.02 at temperatures and wavelengths of 300 to 773 K and 1.0 to 14.6 micrometers. At this low emittance value, the polished substrate emits a negligible amount of heat flux from its surface and radiant emission is only from the ceramic. The ceramic specimen was prepared to the desired thickness by using a small grit blaster to erode the material over small areas of about 1 cm^2. Emittance measurements were made at ceramic thicknesses of 0.005, 0.025, and 0.051 centimeter.

Transmittance measurements were made at 300 K and at ceramic thicknesses of 0.005, 0.025, and 0.051 centimeter. The ceramic thickness was again obtained by using a small grit blaster to erode the material over areas of about 1 cm^2. The thinnest ceramic specimen was very fragile and therefore was held between two glass slides. The glass slides had a measured normal transmittance of 0.092, at wavelengths of 1 to 3 micrometers and were opaque at longer wavelengths. Glass slides were not needed to hold the thicker specimens. Table I presents further details of conditions for normal spectral transmittance and emittance measurement with the ceramic disk specimens.

RESULTS AND DISCUSSION

Figure 8 presents normal spectral emittance data of the isothermal NASA Ceramic Thermal Barrier Coating System (TBC) with stabilized zirconia ceramic coating thickness as parameter. Changes in wavelength of thermal radiation and thickness of ceramic coating greatly affect TBC spectral emittance. The TBC is spectrally selective with emittances varying continuously from low values at the shorter wavelengths to high

values at increasing infrared wavelengths. The measured TBC emittance is reduced at the shorter infrared wavelengths as ceramic coating thickness is increased. The reasons for these trends will be described in the next paragraph.

Spectral Radiation Properties

Yttria-stabilized zirconia. - Figure 9 shows spectral values of normal emittance, transmittance, and reflectance properties for only the yttria-stabilized zirconia ceramic. A study of these three properties at isothermal temperature conditions will aid in understanding the reasons for emittance and reflectance variations associated with the entire TBC system. Figure 9 shows that the stabilized zirconia emittance is spectrally selective with emittance continuously increasing from values of 0.3 or less at 1 micrometer of wavelength to nearly 1.0 at wavelengths of 8 to 14 micrometers. At the wavelengths of 8 to 14 micrometers where the zirconia emittance is about 1.0, there is negligible transmittance through the zirconia and no reflection from it. (The sum of the values of the three spectral properties always equals 1.0.)

At a ceramic thickness of 0.005 centimeter, the material exhibits a high measured value of transmittance equal to 0.82 at wavelengths of 1 to 3 micrometers (fig. 9(a)). As thickness is increased to 0.033 and 0.051 centimeter (figs. 9(b) and (c), respectively, the transmittance at these wavelengths goes to zero and reflectance substantially increases.

TBC system. - Measurements made with the spectrometer showed no temperature variation of the TBC normal emittance at given wavelengths and thicknesses. Also, the measurements made with the infrared radiation pyrometer on flat samples and uncooled blade leading edge samples showed no temperature variation of emittance at a wavelength of about 2.3 micrometers and at angles from 0° to 88° measured from the normal to the surface. Thus the assumptions made in the section ANALYSIS that the emittance is temperature invariant and that the measured normal spectral emittance equals the hemispherical spectral emittance are reasonable for the TBC.

Figure 8 shows that the TBC is spectrally selective with emittance continuously increasing from values of 0.42 or less at 1 micrometer of wavelength to nearly 1.0 at wavelengths of 8 to 14.5 micrometers. This trend is predominently due to the spectral selectivity of the ceramic emittance.

At shorter wavelengths of 1 to 5 micrometers, the bond coating emittance is about 0.64 to 0.69, but the TBC spectral emittance decreases as ceramic thickness increases. (TBC emittance decreases to a value as low as 0.30 at a wavelength of 1 micrometer when the ceramic thickness increases to 0.033 centimeter.) This trend is mostly due to a decrease of bond coating heat flux transmitted through a translucent ceramic of in-

creasing thickness. At zirconia thicknesses greater than 0.033 centimeter, no radiant energy from the bond coating can be transmitted through the now opaque ceramic. The decreased emittance (i.e., increased reflectance) shown in figures 8 and 9 at ceramic thicknesses greater than 0.033 centimeter is attributable to an increase in the number of voids (i.e., a larger number of scattering centers) as the volume of plasma-sprayed ceramic material becomes greater. These voids are shown in figure 1.

Figure 9(a) shows that 0.82 is the normal spectral transmittance of a 0.005-centimeter-thick piece of yttria-stabilized zirconia ceramic material directly measured in the spectrometer at wavelengths of 1 to 3 micrometers. This transmittance, which includes scattering effects, agrees with a value of 0.83 calculated with equation (6b) at the same ceramic thickness and radiation wavelength conditions. For example, at a wavelength of 2 micrometers and a ceramic thickness of 0.005 centimeter, substituting emittance values of ceramic ($\varepsilon_{1,n,\lambda}$), TBC system ($\varepsilon'_{n,\lambda}$), and filled bond coating ($\varepsilon_{0,n,\lambda}$) equal to 0.06 (fig. 9(a)), 0.45 (fig. 8), and 0.47 (fig. 8), respectively, into equation (6a) results in $\tau_{1,n,\lambda} = 0.83$. Comparisons at other wavelengths also showed good agreement between direct transmittance measurement values and values calculated with equation (6a).

Effect of other parameters. - The use of calcia, magnesia, or yttria for stabilizers at the percent by weight quantities given in table I had no effect on the emittance of either rough or smooth zirconia. Although clean, plasma-sprayed stabilized zirconia colors varied from light yellow to light yellow-orange, there was no emittance change of these materials at infrared wavelengths of 0.7 to 14.7 micrometers.

Figure 10 shows the effect of particulate deposition from the combustion gases on the TBC after tests lasting 150 hours in the research turbojet engine. Comparison of coating spectral emittance before and after the tests showed only small changes.

Hemispherical Radiation Properties

Figure 11 presents data points of hemispherical total emittances which were calculated using equation (1) and the measured normal spectral emittance data given in figure 8. The data in figure 11 are correlated with the following equations:

$$\varepsilon'_{h,t} = 4.52e^{44x}\, T^{-(7.25x+0.28)},\quad 0.051 = x\ (\text{cm}) \geq 0.00 \tag{10}$$

and

$$\varepsilon'_{h,t} = 42.25\, T^{-0.65},\quad x > 0.051\ \text{cm} \tag{11}$$

When evaluating $\varepsilon'_{h,t}$ at isothermal conditions, the temperature T in equations (10) and (11) is the isothermal value T'_c. At nonisothermal conditions, such as exist in cooled coated turbines with a temperature drop through the translucent coating, the surface temperature T'_{SUR} is used. Justification for use of T'_{SUR} in current gas turbine engines is presented in the section Nonisothermal Conditions.

The total hemispherical absorptance $\alpha'_{h,t}$ is obtained from equation (10) or (11) by substituting the temperature of the incident or gray source radiation, T_s for T and $\alpha'_{h,t}$ for $\varepsilon'_{h,t}$.

Applying the results of figure 11 (eqs. (10) and (11)) to an advanced gas turbine engine at a combustion gas temperature of 2200 K (ref. 5) gives values for the hemispherical total absorptance of 0.29 and 0.44 at ceramic thicknesses of 0.051 and 0.015 centimeter, respectively (eq. (3)). Because reflectance of the TBC system is equal to 1.0 minus absorptance, the corresponding values of reflectance are 0.71 and 0.56. Evidence of the benefits of this high reflectance was obtained in reference 19 which showed a large reduction of aircraft gas turbine combustor liner temperatures when the TBC was used.

Nonisothermal Conditions

Calculations using equations (7) and (8) at the current aircraft gas turbine engine conditions showed that the values of effective total temperature $\overline{T}$ (eq. (8)) and the ceramic gas side surface temperature T'_{SUR} are not much different. The calculated value of $\overline{T}$ is 1320 K which is 2.7 percent below the gas-side surface temperature (1356 K) of the TBC. The hemispherical total emittance at both of these temperatures is 0.51 (fig. 11 or eq. (10) with $x = 0.020$ cm). This agreement suggests that the gas-side surface temperature is the more practical reference temperature for calculation of total radiant heat emission on ceramic coated blade, vane, combustor, and shroud components operating at these conditions.

Predictions at engine conditions indicate that changes in flux with coating thickness variations are significant enough to permit detection of ceramic coating thickness variation in engine operation with pyrometers. As the coating wears away, flux variations arise from simultaneous increases of TBC spectral emittance and decreases of coating temperature. At current aircraft gas-turbine conditions (combustion gas temperature and pressure of 1544 K and 2.53×10^6 pascals, respectively), the radiant heat flux could decrease about 6 percent as ceramic coating thickness varies from 0.020 to 0.010 centimeter. Most pyrometers can sense this change of heat flux.

CONCLUDING REMARKS

The results of this study provide the designer of coated, cooled gas turbine hardware with correlating equations for the total hemispherical absorptance and emittance properties of the NASA Ceramic Thermal Barrier Coating (TBC) system over a range of temperatures and ceramic coating thicknesses necessary for calculating radiation heat loads. Calculation of the radiant heat transfer within the ceramic coating showed that the designer can, with little loss of accuracy, use the gas-side ceramic coating surface temperature in radiation heat load analysis. The TBC has a high reflectance and as a consequence can significantly reduce the radiant heat load from the combustion gas on cooled aircraft gas turbine engine components.

Measurements show that the TBC is spectrally selective with normal emittance continuously increasing from values of 0.4 or less at 1 micrometer of wavelength to nearly 1.0 at wavelengths of 8 to 14.6 micrometers.

At shorter wavelengths, the TBC spectral emittance decreased as ceramic coating thickness increased. At ceramic layers of 0- to 0.033-centimeter thickness, the coating system emittance decrease is attributed to bond coating emittance being higher than the ceramic coating emittance and to a decrease in transmittance of bond coating heat flux through the ceramic as its thickness is increased. This trend was verified in direct transmittance experiments with the ceramic alone which showed that its transmittance decreases to zero as its thickness is increased from 0.0 to 0.033 centimeter. At ceramic thicknesses of 0.033 to 0.076 centimeter, the TBC emittance variations mostly result from emittance and reflectance changes of only the ceramic overcoating. The variation of emittance at ceramic thicknesses below 0.033 centimeter are significant enough to permit radiation-pyrometer detection of changes in ceramic thickness due to erosion or other causes during engine operation.

Other results showed that the normal and hemispherical spectral emittance property did not change as TBC temperature was varied from 300 to 1590 K. Also, this property did not change when zirconia ceramic stabilizer (Y_2O_3, MgO, and CaO), surface roughness (1 to 10 μm), surface color (very light yellow to light yellow orange), and view angle (0° to 88° from the normal to the surface) were varied.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 9, 1978,
505-04.

APPENDIX - SYMBOLS

b_1 constant in eq. (1), 1.2864×10^{-15} W/(cm^2)(μm)(K^5)

C_1 constant in Planck's spectral energy distribution, 3.7413×10^4 (W)(μm^4)/cm^2, eq. (5)

C_2 constant in Planck's spectral energy distribution, 14 388 (μm)(K), eq. (5)

Q total heat flux

r reflectance (scattering included)

x thickness of ceramic coating (see eqs. (10) and (11))

T absolute temperature

W_λ spectral intensity of blackbody

W_{λ_m} maximum spectral intensity of blackbody (ref. 9)

α absorptance (scattering included)

ε emittance (scattering included)

λ wavelength

σ Stefan-Boltzman constant, 5.669×10^{-12} W/(cm^2)(K^4)

τ transmittance (scattering included)

Superscripts:

' NASA Ceramic Thermal Barrier Coating (TBC) system

- evaluated at effective temperature of the TBC system with temperature drop through translucent ceramic

Subscripts:

c refers to isothermal temperature of NASA Ceramic TBC

h hemispherical

m maximum

n normal

SUR gas side surface of NASA Ceramic TBC (fig. 3)

s source (combustion flame or gas with high soot density)

T_c property is evaluated at isothermal coating temperature

T_s	property is evaluated at source temperature (combustion flame or gas with high soot density)
t	total
0	ceramic filled bond coating
1, 2, 3, 4	denotes subvolumes of ceramic coating
λ	spectrally (wavelength) dependent

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TABLE I. - MATERIALS, CONDITIONS, AND

Type of coating	Material			Conditions		
	Zirconia stabilizer (plasma-sprayed)	Bond coating (plasma-sprayed)	Substrate	Ceramic thickness, x, cm[a]	Temperature, K	Wavelength, μm
NASA developed Ceramic Thermal Barrier Coating (TBC)	Yttria, 12 wt.%	Ni-16Cr-6Al-0.5Y; thickness - 0.010 cm	Inconel alloy 718 sheet	0, 0.015, 0.025, 0.033, 0.051, 0.074	775, 1265	1 to 14.6
					1530	2, 5, 8, 12
				0, 0.025, 0.051	775, 1530	2, 3
			B-1900 (leading edge of coated blade)	0.025	775, 1265, 1580	2, 3
			B-1900 (sample from blade tested in research engine)	0.025	775, 1265	1 to 14.6
					1530	2, 5, 8, 12
			Inconel alloy 718 sheet	0, 0.051	300	0.4 to 1.4
With other zirconia stabilizers	Calcia, 5 wt.%	Ni-16Cr-6Al-0.5Y; thickness - 0.010 cm	Inconel alloy 718 sheet	0.051	1265	1 to 14.6
	Magnesia, 3.2 wt.%	Ni-16Cr-6Al-0.5Y; thickness - 0.010 cm	Inconel alloy 718 sheet	0.051	1265	1 to 14.6
Alloy bond coating on substrate	----------	NiCrAlY	Inconel alloy 718 sheet	----------	775, 1265	1 to 14.6
					1530	2, 5, 8, 12
Zirconia ceramic disk specimen	Yttria, 12 wt.%	None	Clamped between glass	0.005	300	1 to 3
			No substrate	0.025, 0.051	300	1 to 14.6
			Clamped onto mirror surface	0.005, 0.025, 0.051	900	1 to 14.6

[a]Thickness measured from above ceramic filled bond coating surface (see fig. 1). As-plasma-sprayed and

INSTRUMENTS OF EXPERIMENTAL INVESTIGATION

Conditions			Instruments and measured property		
Measurement angle from normal to surface, deg	Ceramic surface condition	Color of ceramic in daylight	Emittance	Reflectance	Transmittance
Near zero	Rough (as-plasma-sprayed) and polished	Light yellow orange to very light yellow with black specks	Spectrometer	None	None
Near zero	Rough (as-plasma-sprayed) and polished	Light yellow orange to very light yellow with black specks	Spectrometer	None	None
0 to 80	Rough (as-plasma-sprayed) and polished	Light yellow orange to very light yellow with black specks	Radiation pyrometer and spectrometer furnace	None	None
0 to 80	Rough (as-plasma-sprayed) and polished	Light yellow orange to very light yellow with black specks	Radiation pyrometer and [illegible]-lined electric furnace	None	None
Near zero	Rough with particulate deposition of rust	Light rust color over very light yellow with black specks	Spectrometer	None	None
Near zero	Rough with particulate deposition of rust	Light rust color over very light yellow with black specks	Spectrometer	None	None
Near zero	Smoothed	Light yellow orange with black specks	----------	Reflectometer	None
Near zero	Smoothed	Light yellow orange with black specks	Spectrometer	None	None
Near zero	Smoothed	Light yellow orange with black specks	Spectrometer	None	None
Near zero	Rough (as-plasma-sprayed) and polished	Black	Spectrometer	None	None
Near zero	Rough (as-plasma-sprayed) and polished	Black	Spectrometer	None	None
Near zero	Rough (as-plasma-sprayed) and polished	0.0051-cm-thick specimen was transparent with essentially no color, 0.0254- and 0.0509-cm-thick specimens were light yellow orange with black specks	----------	None	Spectrometer
Near zero	Rough (as-plasma-sprayed) and polished	0.0051-cm-thick specimen was transparent with essentially no color, 0.0254- and 0.0509-cm-thick specimens were light yellow orange with black specks	----------	None	Spectrometer
Near zero	Rough (as-plasma-sprayed) and polished	0.0051-cm-thick specimen was transparent with essentially no color, 0.0254- and 0.0509-cm-thick specimens were light yellow orange with black specks	Spectrometer	None	None

polished thickness variations from average values given in this table are 0.003 and 0.002 cm, respectively.

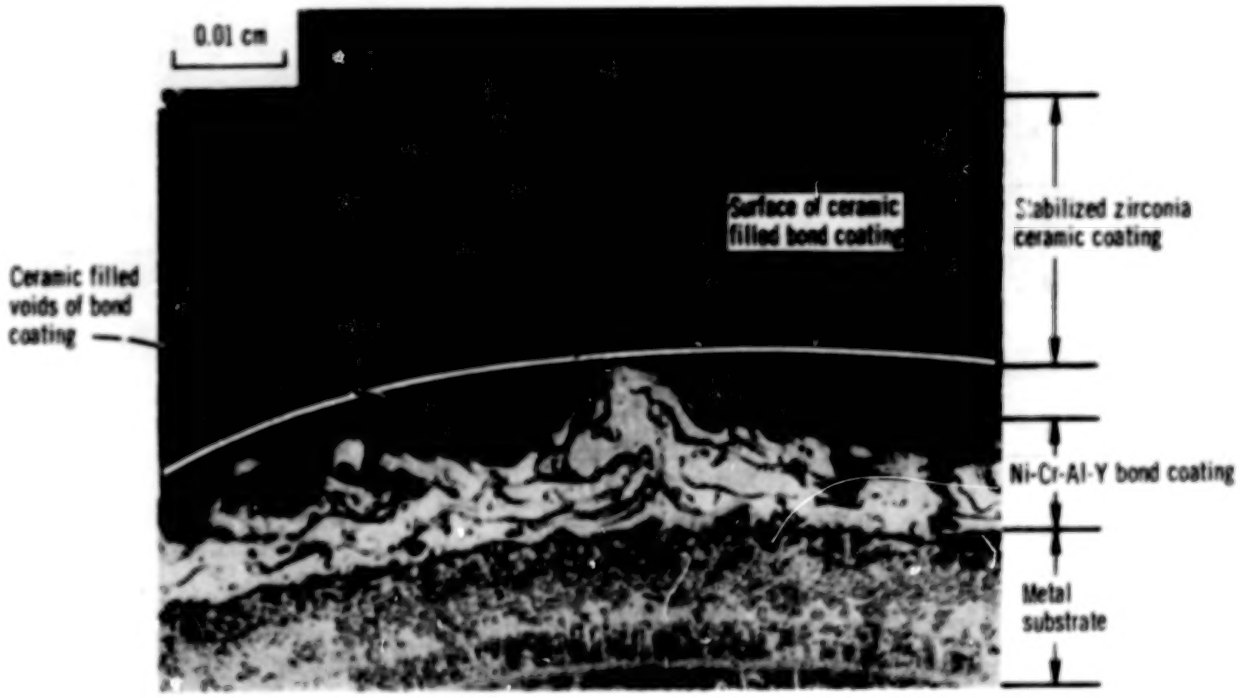


Figure 1. - Microstructure of NASA Ceramic Thermal Barrier Coating (TBC).

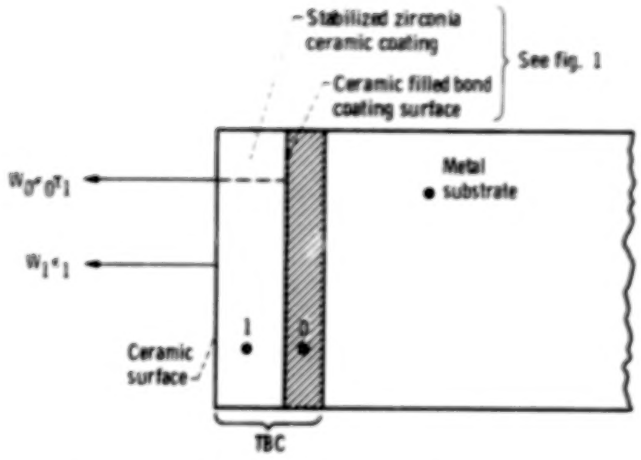


Figure 2. - Schematic of radiant heat flow through NASA Ceramic TBC at isothermal conditions.

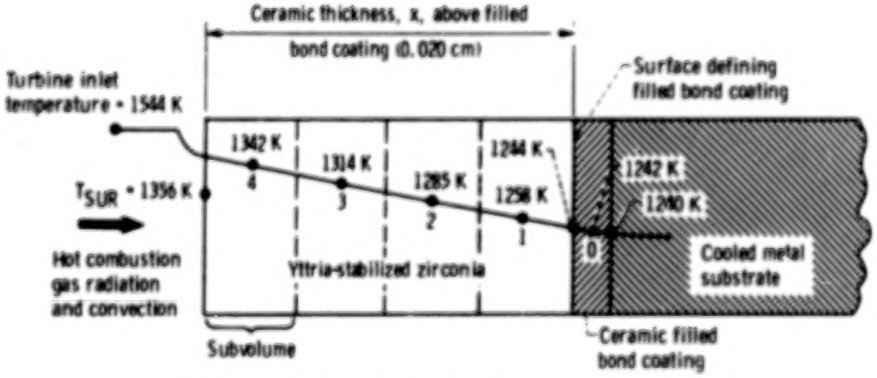
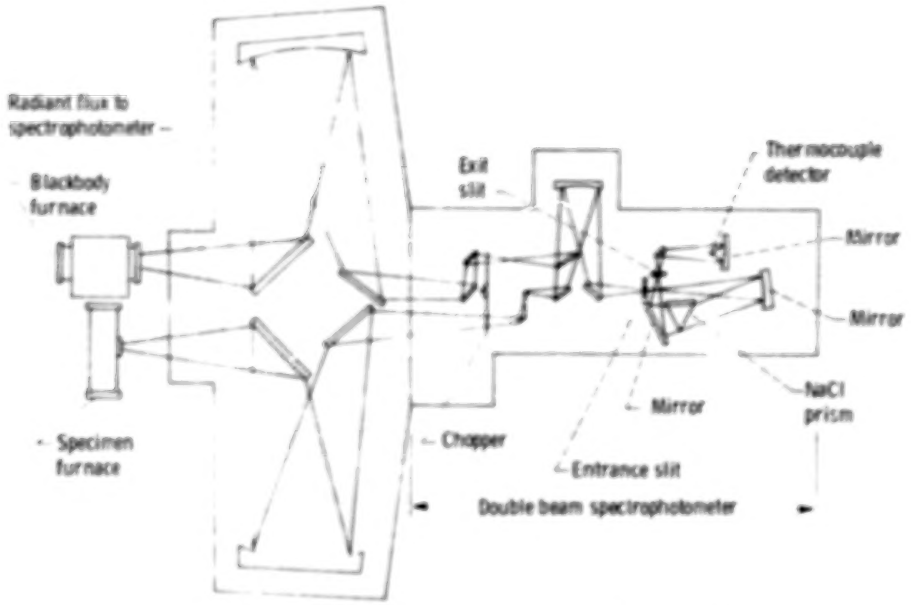
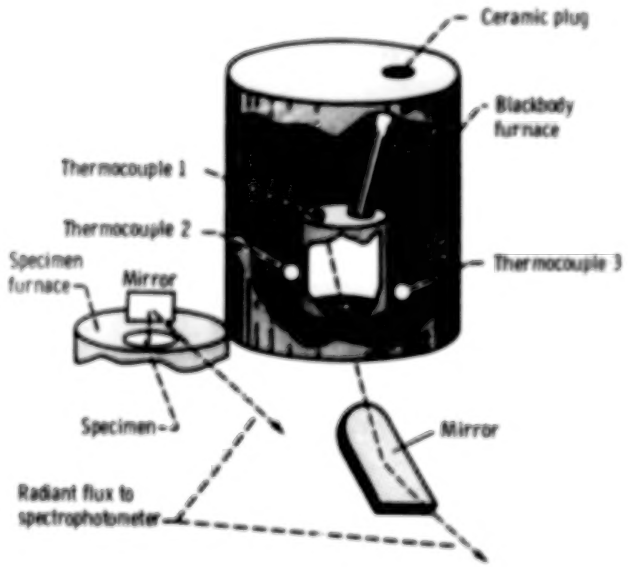


Figure 3. - NASA Ceramic TBC at nonisothermal conditions with four ceramic subvolumes.



(a) Spectrometer (double-beam spectrophotometer with furnace attachments).



Thermocouple			Wavelength, μm	Aluminum specimen temperature setting, K
1	2	3		
Blackbody temperature setting, K				
773	773	773	1 to 14.7	773
1265	1270	1257	1 to 14.7	1265
1530	1550	1540	2, 5, 8, and 12	1530

(b) Schematic drawing and temperatures in blackbody and specimen furnaces.

Figure 4. - Experimental arrangement for spectrometers.

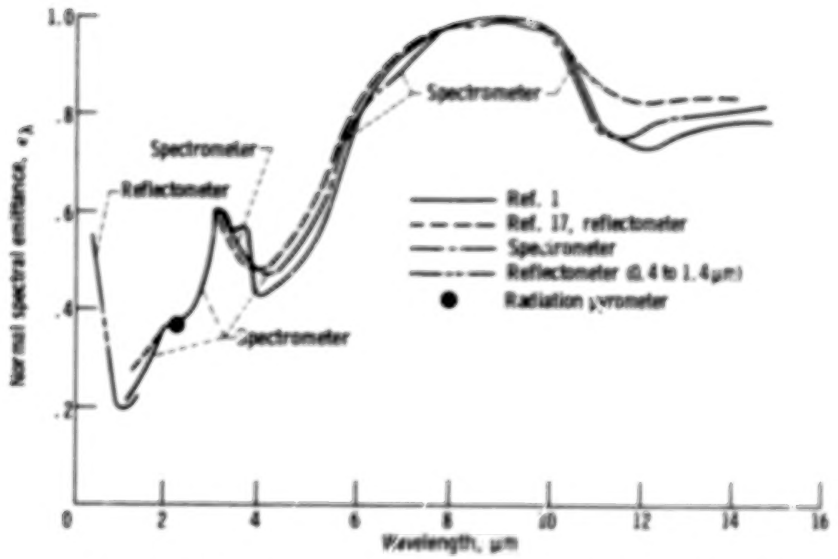


Figure 5. - Isothermal spectral emittance of plasma-sprayed alumina (0.051 cm thick). (Note that ϵ_λ invariant over a range of temperature measurements of 300 to 1530 K.)

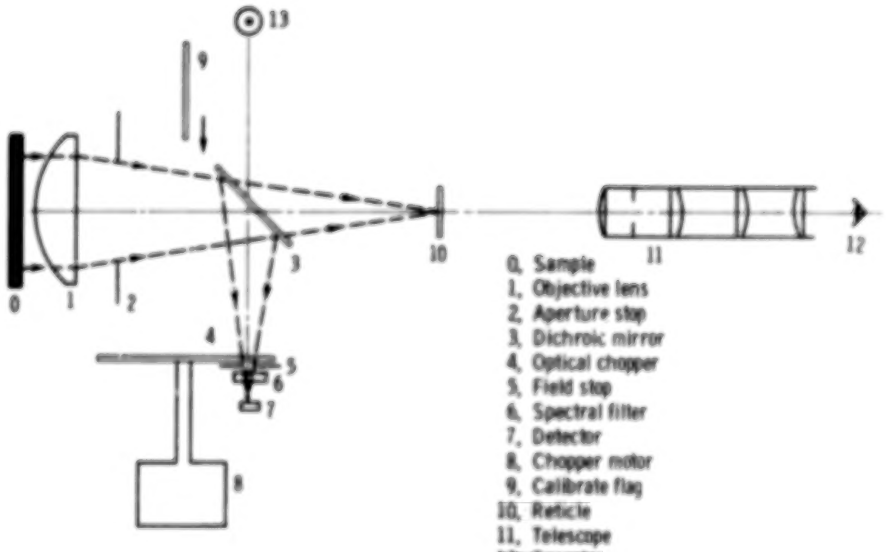


Figure 6. - Experimental arrangement for infrared radiation pyrometer.

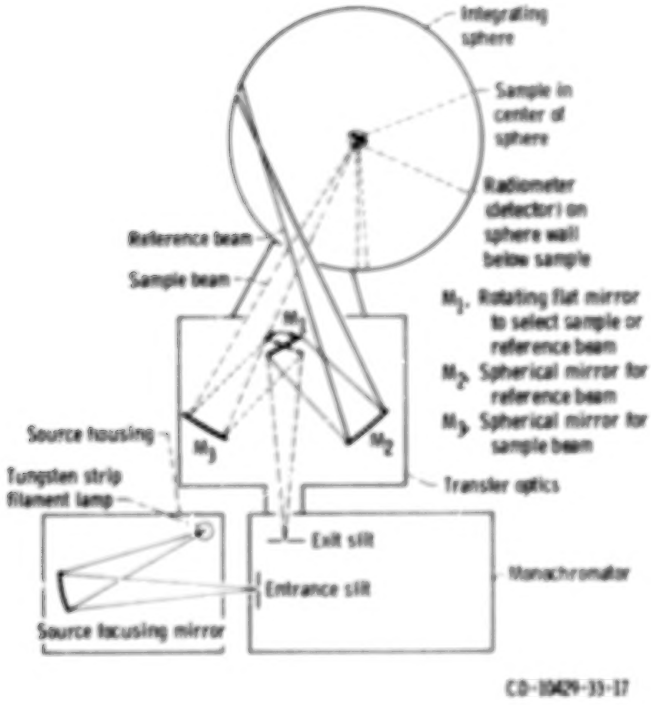


Figure 7. - Experimental arrangement for integrating sphere reflectometer (ref. 18).

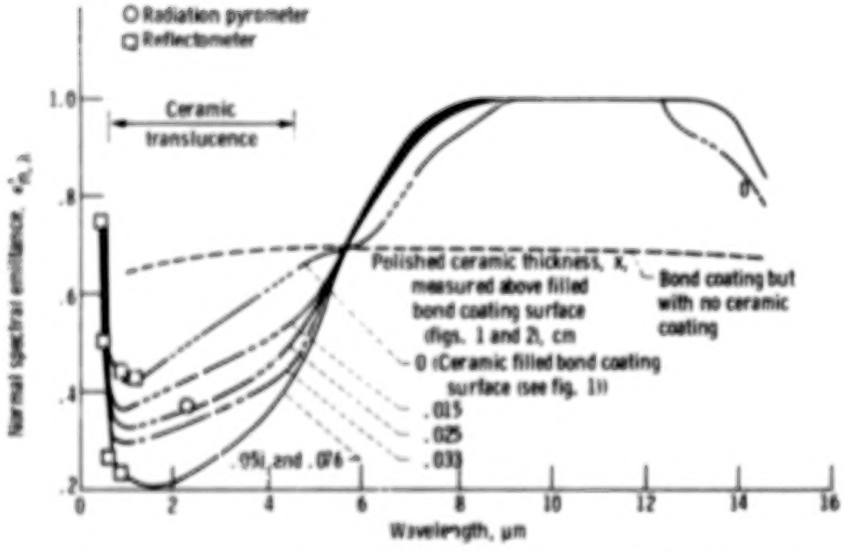


Figure 8. - Measured emittance of the NASA Thermal Barrier Coating. Note that ϵ_λ invariant over range of temperature measurements of 300 to 1590 K.

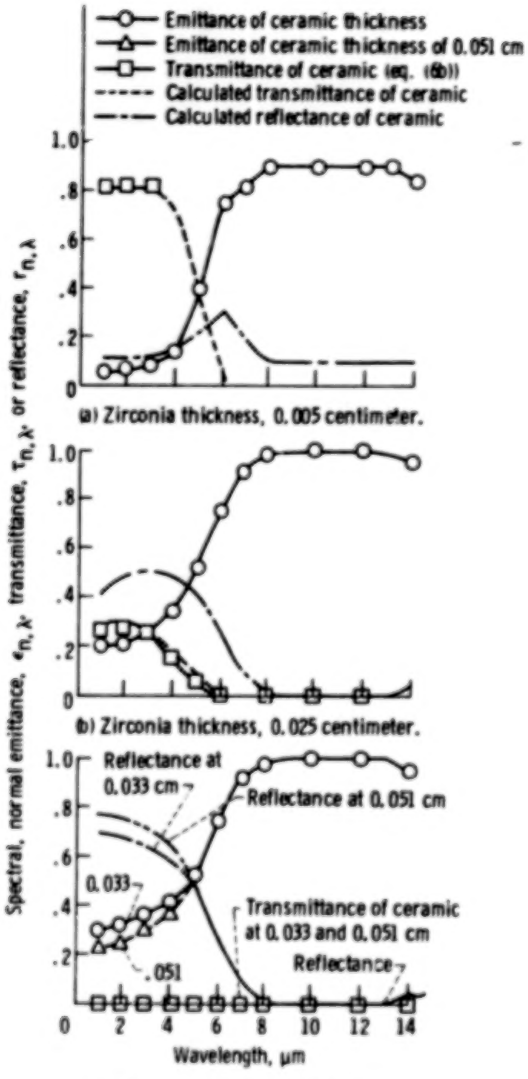


Figure 9. - Radiation properties of plasma-sprayed zirconia ceramic.

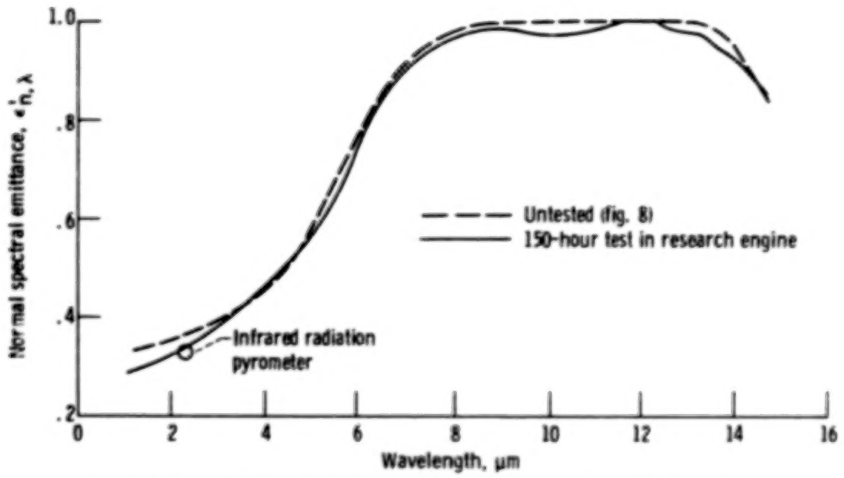


Figure 10. - Measured emittance of untested and engine tested NASA Ceramic Thermal Barrier Coating. Ceramic thickness, 0.0254 centimeter.

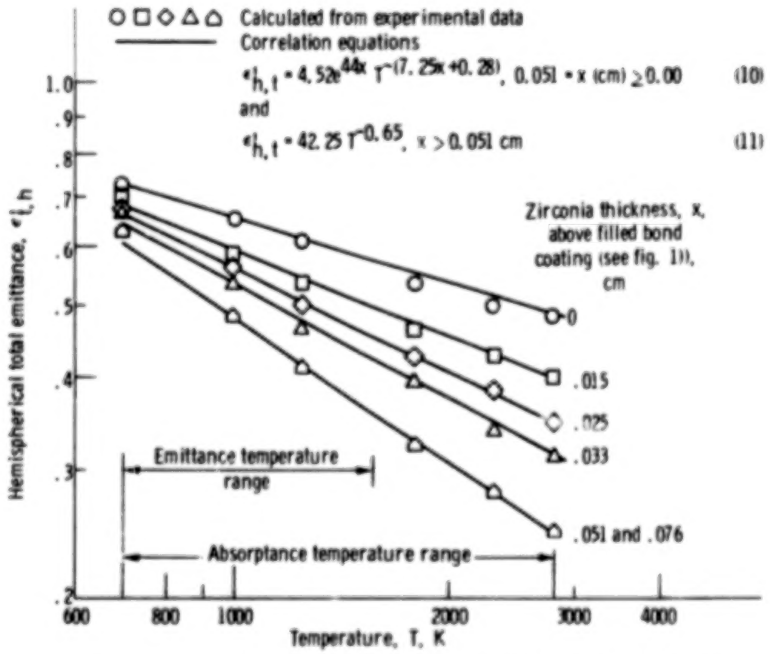


Figure 11. - Total hemispherical emittance of NASA Ceramic Thermal Barrier Coating as function of temperature and thickness.

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15. Supplementary Notes

16. Abstract

Normal spectral emittance measurements were made on a two-layer ceramic thermal barrier coating system developed at the NASA Lewis Research Center. This coating system consists of a metal substrate, a NiCrAlY bond coating and a yttria-stabilized zirconia ceramic coating. Spectral emittance data were obtained for the coating system at temperatures of 300 to 1590 K, ceramic thicknesses of zero to 0.076 centimeter, and wavelengths of 0.4 to 14.6 micrometers. The data were transformed into total hemispherical emittance values and correlated with respect to ceramic coating thickness and temperature using multiple regression curve fitting techniques. These techniques produced equations which can be easily used by the designer to calculate the hemispherical total absorptance and emittance of this coating system. The results show that the NASA Ceramic Thermal Barrier Coating System is highly reflective and, therefore, can significantly reduce radiation heat loads on cooled gas turbine engine components. Calculation of the radiant heat transfer within the nonisothermal, translucent ceramic coating material shows that the designer, with little loss of accuracy, can use the gas-side ceramic coating surface temperature in heat transfer analysis of radiation heat loads on the coating system.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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